MARS AVATAR PROJECT

Control Without Presence

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A conceptual study of a telepresence architecture for the remote exploration of Mars

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Executive Summary

The Mars Avatar Project (MAP) is a conceptual architecture for exploring Mars in which humans retain full intellectual control from Earth while a fleet of specialized robotic avatars provides physical presence on the surface. The one-way signal delay of 4–22 minutes is treated not as an obstacle but as a design condition: the operator transmits goals, and onboard autonomy determines how to achieve them.

The contribution. Nearly every component of this architecture has already been demonstrated in isolation — goal-based commanding on NASA rovers (AutoNav, AEGIS), supervisory telepresence from orbit (ESA METERON), immersive avatar interfaces (ANA Avatar XPRIZE). What no program has built is the layer that coordinates a heterogeneous fleet under full interplanetary latency. That layer — Mission AI — is the project's principal original contribution: a five-layer reference architecture, a formal goal-package protocol, graduated decision classes (A/B/C) with a controllable trajectory of increasing autonomy, and measurable quality metrics (Chapter 6).

The economics. A Stage III fleet of ten specialized platforms plus two orbital relays is estimated at ≈ $14–23B over a ten-year operating cycle, against ≥ $100B for the lower bound of a crewed program — while fitting within the proven ≤1 t entry-descent-landing envelope that crewed architectures exceed by an order of magnitude (Chapter 11). The cancellation of Mars Sample Return after its estimate grew to $8–11B illustrates the cost of return architectures; MAP avoids them by design — avatars do not return.

The asset. Unlike an expedition, the architecture is a transferable technology: moving from Mars to the Moon, Europa, Titan, or an asteroid changes parameters (delay, gravity, environment), not principles. Mars is not the destination; it is the first and most instructive proving ground. A system that works under a 22-minute delay will work anywhere (Chapter 13).

The path. A staged roadmap — terrestrial prototype (2026–2030) → lunar demonstration (2030–2035) → first Mars missions (2035–2045) → robotic infrastructure → support for crewed expeditions — with explicit, measurable transition criteria at each step (Chapter 10). MAP does not replace crewed missions; it makes them cheaper and safer by taking on the preparatory and routine work first.

Chapter 1. Introduction

1.1 Introduction

Humanity is entering a new era of space exploration. Over recent decades, robotic missions have significantly expanded our knowledge of the Solar System, and automated spacecraft have proven their effectiveness in studying the Moon, Mars, asteroids, and other celestial bodies.

Despite these successes, crewed expeditions beyond near-Earth space remain extremely difficult. Prolonged flights require protecting the crew from cosmic radiation, building reliable life-support systems, solving the medical problems of long-term weightlessness, and ensuring a safe return to Earth. These factors substantially increase the cost, complexity, and risk of such missions.

At the same time, robotics, artificial intelligence, computer vision, autonomous navigation, and human–machine interfaces are developing rapidly. The combination of these technologies opens the possibility of considering a different approach to planetary exploration.

This document presents the concept of the Mars Avatar Project — an architecture in which the human retains key decision-making while intelligent robotic avatars provide physical presence on the surface of Mars. In such a system, autonomous algorithms compensate for the unavoidable communication delay between Earth and Mars, performing local actions within the goals set by the operator.

It is important to emphasize that this document is not the design of a ready-made space mission. It is a conceptual study whose aim is to propose a coherent roadmap for developing the technologies required for such an architecture. The work deliberately distinguishes among:

1. existing technologies;
2. projected directions of development;
3. long-term research hypotheses.

This approach makes it possible to discuss the idea in an engineering context without conflating the confirmed capabilities of present-day technology with more distant scientific prospects.

1.2 Purpose of the Document

The purpose of this White Paper is to present a conceptual architecture for a telepresence system for exploring Mars, integrating advances in robotics, artificial intelligence, space communication, and human–machine interfaces. The document seeks to answer the following questions:

- Which technologies already make it possible to implement individual elements of such a system?
- Which engineering problems remain unsolved?
- What might a realistic path for developing such technologies over the coming decades look like?
- What are the advantages and limitations of an approach based on robotic avatars?

1.3 Scope of Application

The proposed architecture may be considered for a variety of scenarios:

- scientific study of the Martian surface;
- construction of automated infrastructure;
- preparation for future crewed missions;
- equipment servicing;
- resource extraction;
- exploration of other planets, moons, and asteroids.

1.4 Mission versus Technology

The key distinction underlying this document is the distinction between a mission and a technology.

A crewed expedition is a mission: enormous resources are spent to deliver specific people to a specific place and bring them back. The result of an expedition cannot be reused — every subsequent flight requires nearly the same expenditure as the previous one. The history of Mars Sample Return demonstrated this in miniature: it was precisely the return architecture (ascent from Mars, orbital rendezvous) that became the principal driver of cost growth from ~$3–4B to $8–11B and the reason for the program's cancellation [22].

A telepresence architecture is a technology: once created, the loop of “goal → autonomous execution → report” is a transferable asset. In moving from Mars to the Moon, Europa, Titan, or an asteroid, only the parameters change — the magnitude of the signal delay, gravity, the properties of the environment. The architecture itself — Mission AI, the goal-package protocol, the decision categories, the degradation hierarchy — remains unchanged.

The question of this document is therefore framed not as “how to reach Mars” but as “how to build a universal technology of presence.” In this framing, Mars is not the goal but the first and most instructive proving ground: a planet of maximal scientific return, with a communication delay large enough to test the architecture honestly. A system that works under a 22-minute delay will work anywhere.

Chapter 2. The Challenge of Exploring Mars

2.1 Why Mars?

Mars remains one of the most attractive targets for human exploration. Compared with other objects in the Solar System, it offers a number of advantages: a day length close to Earth's, the presence of an atmosphere (albeit very thin), reserves of water ice, and significant scientific potential.

Studying Mars can help answer fundamental questions about the origin of planets, the evolution of climate, and the possibility of life beyond Earth. In addition, the experience gained may become the basis for future expeditions to more distant objects in the Solar System. However, Mars remains an extremely difficult environment for human work.

2.2 Principal Engineering Challenges

Cosmic Radiation

Beyond Earth's magnetic field, the crew is exposed to galactic cosmic rays and solar energetic particles. Even with modern protective measures, prolonged stays in interplanetary space increase health risks, including the likelihood of developing cancers, nervous-system damage, and other long-term consequences [1][2][3]. For robotic systems this problem is far less critical, since they require no biological shielding and can be designed with radiation-hardened electronics.

Mission Duration

A typical crewed expedition to Mars may last more than two years, accounting for the flight, the wait for a favorable return window, and the journey back. Throughout this time it is necessary to provide:

- food;
- water;
- oxygen;
- medical care;
- psychological support;
- maintenance of life-support systems.

Each additional day increases the complexity of the mission.

Limited Human Capabilities

Even after a successful landing, a human faces serious limitations:

- fatigue;
- the need for rest;
- limited duration of extravehicular activity;
- the effects of reduced gravity;
- the risk of errors under high workload.

Robotic systems also have limitations, but they can operate far longer without breaks, provided they are supplied with power and maintenance.

2.3 Communication Delay

One of the key engineering problems is the distance between Earth and Mars. Depending on the relative positions of the planets, a signal takes roughly 4–22 minutes one way [4][5]. This means that direct real-time control of a robot is impossible. For example:

- the operator presses a button;
- the command reaches Mars after several minutes;

- the robot performs the action;
- confirmation returns after several more minutes.

The full cycle can take tens of minutes. Consequently, the traditional teleoperation model is not suitable for interplanetary missions.

2.4 Why Is Simply Increasing Communication Speed Not Enough?

No advance in data-transmission technology can remove the fundamental limitation associated with the speed at which electromagnetic waves propagate. Even ideal communication is limited by the speed of light. Consequently, the architecture of future systems must treat the unavoidable delay as a basic physical condition rather than a temporary technical problem. This leads to the necessity of using autonomous algorithms capable of performing local actions without constant human involvement.

2.5 The Cost of Crewed Missions

Crewed expeditions require complex systems:

- heavy launch vehicles;
- landing modules;
- habitation modules;
- resource reserves;
- crew-protection systems;
- return vehicles.

Each of these components substantially increases the cost of the program. Robotic missions also require significant investment; however, they need no life-support systems and can be specialized for particular tasks, which potentially allows the infrastructure to be scaled more flexibly.

2.6 Problem Statement

Given the limitations listed above, a question arises:

> *Is it possible to create a system in which the human retains intellectual control of the exploration while physical presence on the surface is provided by a network of autonomous robotic avatars?*

This document treats this idea as a conceptual architecture that combines modern advances in robotics, artificial intelligence, and space communication. The goal is not to replace future crewed missions but to explore whether such an approach can complement them, improving the safety, flexibility, and effectiveness of Mars exploration.

Chapter 3. Positioning Relative to Existing Work

> *A concept earns credibility not by claiming novelty, but by showing precisely where it stands among its predecessors.*

3.1 Why This Chapter Is Needed

The idea of commanding remote robots at the level of goals rather than individual movements is not new. Several elements of the Mars Avatar Project architecture have already been demonstrated in operational NASA and ESA missions, in orbital experiments, and in ground-based telepresence competitions. The absence of an honest comparison with this prior work is a characteristic weakness of visionary documents, and it undermines the trust of a technical audience. The purpose of this chapter is to show which components of the concept have already been validated in practice, by which programs, and what precisely distinguishes the contribution of the Mars Avatar Project.

3.2 Goal-Based Commanding in Operational Mars Missions

Control of NASA's Mars rovers has, from the outset, relied not on teleoperation but on daily command packages: operators build a plan for the sol, the rover executes it autonomously, and results return to Earth in time for the next planning cycle. The AutoNav system on the Perseverance rover extended this model to autonomous route selection: as shown later in Chapter 5, roughly 88% of the traverse was completed without direct operator involvement [8][9].

In addition, the AEGIS system running on Curiosity and Perseverance autonomously selects science targets for spectrometers without waiting for commands from Earth [28]. The principle “goal → autonomous execution → report” is therefore not a hypothesis but operational practice in planetary missions. The Mars Avatar Project extends it from a single vehicle to a coordinated fleet.

3.3 ESA METERON and the Analog-1 Experiment

The closest experimental predecessor is the ESA METERON program (Multi-Purpose End-To-End Robotic Operation Network, 2011–2019), in which astronauts aboard the ISS controlled robots on the ground, modeling a “crew in orbit — robots on the planet's surface” scenario.

- **Kontur-2 and Haptics-1/2** — experiments with force-feedback (haptic) control over an orbital communication link.
- **SUPVIS Justin (2017–2018)** — supervisory control of the humanoid robot Justin (DLR): the astronaut set goal-level tasks through a tablet interface, and the robot executed them autonomously [17].
- **Analog-1 (November 2019)** — astronaut Luca Parmitano, aboard the ISS, controlled the Interact rover at a test site in the Netherlands, including soil sampling with haptic feedback [15][16].

METERON experimentally confirmed key elements of telepresence, but in a low-latency scenario (orbit-to-surface, fractions of a second). The Mars Avatar Project addresses the opposite regime: the operator remains on Earth, the delay is measured in minutes and is compensated by autonomy rather than by a real-time link.

3.4 NASA HERRO and Low-Latency Telerobotics

The HERRO concept (Human Exploration using Real-time Robotic Operations, NASA Glenn Research Center, ~2009–2011) proposed sending a crew to Mars orbit without landing: astronauts would control surface robots in near-real time, avoiding the risk and cost of landing and ascent [18]. A related line of work is “low-latency telerobotics” research (Lester, Thronson, and others), which treats latency as the dominant factor in the effectiveness of remote work [19]. In 2013, NASA conducted the Surface Telerobotics experiment: astronauts aboard the ISS controlled the K10 rover at Ames Research Center, modeling the operation of a lunar rover from a cislunar station [20].

The fundamental distinction of the Mars Avatar Project: HERRO buys low latency at the price of a crewed interplanetary transit — that is, it retains most of the problems listed in Chapter 2 (radiation, life support, cost). MAP makes the opposite wager: eliminate human transit entirely, accept high latency as a design condition, and close it with autonomy. The two approaches are complementary rather than mutually exclusive: the MAP architecture is compatible with a later addition of an orbital crew as a "near" control layer.

3.5 ANA Avatar XPRIZE and Ground-Based Telepresence

The ANA Avatar XPRIZE competition (2018–2022, a $10 million prize purse) demonstrated the maturity of ground-based avatar systems: teams built robots through which a remote operator could see, hear, move, and manipulate objects; the winner was Team NimbRo of the University of Bonn [21]. The competition confirmed the technical feasibility of immersive interfaces (Chapter 9), but under latency of tens of milliseconds. Its results apply to Stage I of the MAP roadmap (ground demonstrations) but do not transfer directly to the interplanetary case — which further underscores the need for an autonomous layer.

3.6 Commercial Space Robotics

The private sector is actively developing orbital and planetary robotics: GITAI has demonstrated autonomous manipulators inside (2021) and outside (2024) the ISS and is developing lunar robotic platforms [30]; Astrobotic and Intuitive Machines carried out the first commercial lunar landings. This means that part of the MAP hardware base can be built through commercial cooperation rather than by agencies alone.

3.7 Positioning Table

Program / Project	What Was Demonstrated	Latency Regime	MAP's Distinction
NASA rover operations (MER, MSL, Mars 2020) + AutoNav, AEGIS	Goal-based commanding, autonomous navigation and target selection on Mars	Minutes (daily planning cycle)	Fleet of heterogeneous platforms rather than a single vehicle; construction tasks
ESA METERON / Analog-1	Supervisory control and haptic link from orbit	Fractions of a second	Operator on Earth; autonomy instead of a real-time link
NASA HERRO, Surface Telerobotics	Concept and experiment in teleoperation from orbit	Fractions of a second – seconds	No crewed transit; latency as a design condition
ANA Avatar XPRIZE	Immersive avatars, manipulation, telepresence	Tens of milliseconds	Interplanetary latency; goal-based rather than motor control
GITAI, commercial lunar missions	Autonomous manipulators in space, landing platforms	Seconds (Moon)	Possible hardware base; MAP adds fleet coordination

3.8 Statement of Contribution (Novelty Claim)

The comparison shows that nearly every component of the Mars Avatar Project has already been demonstrated in isolation. The concept's contribution is therefore framed not as the invention of new components but as their system integration:

- an architecture for goal-based control of a heterogeneous fleet of specialized platforms from Earth under full interplanetary latency — unlike single rovers and orbital scenarios;

- Mission AI as a coordination layer between the operator and the fleet (detailed in Chapter 6), whereas existing missions are autonomous only at the level of an individual vehicle;
- the objective function of “building infrastructure for future crewed missions,” not merely scientific observation;
- a staged verification roadmap Earth → Moon → Mars with explicit transition criteria (Chapter 10).

Multi-robot coordination under a single intelligent dispatcher is precisely the least-developed area in current programs — and this is the principal space for the project's original contribution.

Chapter 4. The Mars Avatar Project Architecture

4.1 General Concept

The Mars Avatar Project is based on the principle of “Control Without Presence” — control without physical presence. Unlike the traditional model of crewed expeditions, where the human personally performs all actions on the planet's surface, the proposed architecture separates intellectual and physical presence.

The human remains the source of goals, decisions, and scientific analysis, while the robotic system provides direct interaction with the environment. Thus, intelligence remains on Earth, while physical presence is transferred to Mars via autonomous robotic platforms.

4.2 System Architecture

The concept comprises seven interconnected layers, shown in the diagram below.

Fig. 4.1. Architectural diagram of the Mars Avatar Project system

4.3 The Human Layer

The human remains the central element of the entire system. The human:

- defines the scientific tasks;
- sets priorities;
- approves critical decisions;
- analyzes the results obtained;
- intervenes in non-standard situations.

The AI does not make strategic decisions on its own.

4.4 The Control Interface

In the early stages, traditional means are used: computer, VR, AR, joysticks, voice control. As technology develops, brain–computer interfaces (BCI) may be used, allowing faster and more convenient interaction with the system. It is important to note that in the near term BCI is regarded as a supplement, not a mandatory component.

4.5 The Mission Control Center

Mission Control unifies all elements of the system. Its functions:

- task planning;
- priority management;
- resource allocation;
- control of multiple avatars;
- processing of scientific information;
- interaction with operators.

In effect, it is the intelligent dispatcher of the entire expedition.

4.6 Interplanetary Communication

Information is transmitted through existing or future deep-space communication networks. Its main functions: transmission of commands and telemetry, synchronization of system state, verification of data integrity, and encryption. The architecture envisions the use of relay satellites in Mars orbit to improve communication reliability [6][7].

4.7 The Local Artificial Intelligence

This is the key element of the entire concept. Because of the signal delay, it is the local AI that makes decisions within the assigned task. For example, the operator sends the command:

> *"Collect a rock sample near the crater."*

The AI then, on its own:

- plans a route;
- avoids obstacles;
- monitors the robot's stability;
- selects the sampling location;
- assesses safety;
- performs the manipulation;
- returns a report to the operator.

The human defines the goal. The AI determines how to achieve it within the given constraints.

4.8 Robotic Avatars

The architecture provides for the use of specialized platforms: a scientific rover (geology, soil analysis, ice prospecting, sample collection); a construction robot (construction, equipment installation, cable laying, site preparation); a drone (reconnaissance, cartography, inspection of objects, finding safe routes); a laboratory unit (chemical analysis, biological research, sample preparation); and a cargo robot (equipment transport, material delivery, logistics support). Full specifications are given in Chapter 8.

4.9 The Goal-Based Control Principle

Traditional robotics operates with low-level instructions:

> *Turn right. Drive 20 meters. Raise the arm. Lower the arm.*

The Mars Avatar Project proposes a different approach — stating the task at the level of a goal:

> *Explore this area. Collect the most interesting sample. Build a solar farm. Inspect the station.*

Once it receives a goal, the local AI decomposes it into a sequence of actions on its own. This approach makes the system robust to large communication delays.

4.10 Scalability

The architecture is designed as a modular system capable of growing from a single operator and vehicle to a distributed research infrastructure:

- **Today:** 1 operator → 1 robot
- **In prospect:** 1 operator → Mission AI → 10 specialized robots
- **In the long term:** a science team → Mission Control → hundreds of autonomous platforms

This makes it possible to expand the research infrastructure gradually without fundamentally changing the architecture.

4.11 Chapter Conclusions

The proposed architecture is based on a division of roles between human and machine. The human retains responsibility for goals, scientific decisions, and mission control. The local artificial intelligence provides autonomous execution of tasks under the unavoidable communication delay. Robotic platforms become the physical extension of the human's research activity, allowing presence in space to be expanded without a crew permanently residing on the surface of Mars.

Chapter 5. Artificial Intelligence as the Core of the System

> *Artificial Intelligence does not replace the human operator. It extends the operator's ability to act across interplanetary distances.*

5.1 Why Is AI Necessary?

The main limitation of interplanetary control is not computing power and not the bandwidth of communication channels. The main limitation is the speed of light. Even with ideal communication between Earth and Mars, an operator cannot control a robot the way a surgeon controls a robotic system in the next room. A signal delay of several minutes rules out continuous manual control. For this reason, artificial intelligence within the Mars Avatar Project is regarded not as a replacement for the human but as a mandatory architectural element that provides autonomous execution of local actions.

5.2 The Philosophy of the AI Assistant

The project is built on the Human-in-the-Loop principle. This means:

- the human defines the goals;
- the human sets the constraints;
- the human approves critical actions;
- the AI carries out the assigned task on its own.

This approach makes it possible to preserve human control of the mission while compensating for the unavoidable communication delays.

5.3 The Architecture of the Artificial Intelligence

The AI consists of several independent modules, each responsible only for its own area. This reduces system complexity and increases reliability.

Fig. 5.1. The modular architecture of the avatar's artificial intelligence

5.4 Mission Planning AI

The first layer of the AI. Its task is to transform the human's goal into a sequence of actions. For example, the operator sends the command:

> *“Explore the southern part of the crater.”*

Mission Planning AI breaks the task down:

1. Build a map of the area.
2. Select a safe route.
3. Identify interesting geological features.
4. Plan the sampling.
5. Hand off the assignments to the specialized subsystems.

5.5 Navigation AI

The navigation module is responsible for:

- route construction;
- obstacle avoidance;
- terrain analysis;
- rollover prevention;

- energy economy.

Navigation must account for the features of the Martian surface: sandy patches, large rocks, slopes, dust, and limited visibility. A similar approach in principle is already used in the AutoNav system of the Perseverance rover, which on its own assesses or traverses about 88% of the distance covered without direct operator involvement [8][9].

5.6 Manipulation AI

This module controls the manipulators. For example:

- pick up a sample;
- open a container;
- replace a part;
- install a solar panel;
- connect a cable.

If a task cannot be performed safely, the system halts execution and requests new instructions.

5.7 Safety AI

Safety has the highest priority. Every task is checked before execution.

Fig. 5.2. The decision logic of the Safety AI module

The AI must not perform actions that could damage equipment or threaten the entire mission.

5.8 Environment Model

Each robot maintains a digital model of its environment. It includes:

- a map of the terrain;
- the location of obstacles;
- the state of equipment;
- energy resources;
- weather conditions.

This model is continuously updated from sensor data.

5.9 Self-Learning

Within this concept, the robot is not expected to modify its base algorithms on its own during a mission. This is an important engineering constraint. During the execution of mission-critical tasks it is preferable to use pre-validated models. Software updates should occur only after testing and confirmation by specialists.

5.10 Operation During Loss of Communication

If the link with Earth is lost, the robot does not continue performing complex tasks uncontrolled. Possible scenarios:

- stop;
- enter safe mode;
- complete the current safe operation;
- save all data;
- wait for communication to be restored.

Such behavior reduces the likelihood of equipment damage.

5.11 One Operator — Multiple Robots

As autonomy develops, a single operator will be able to control several specialized platforms, interacting not with each mechanism individually but with a shared control system:

> *Operator → Mission AI → Scientific Rover / Construction Robot / Drone / Cargo Robot*

5.12 Limitations of Artificial Intelligence

Despite rapid progress, AI has limitations:

- errors in perceiving the environment;
- uncertainty in non-standard situations;
- dependence on sensor quality;
- limited ability to explain decisions;
- the need for careful validation of algorithms before use.

For this reason, within the project the AI is regarded as a tool to support mission execution, not as a fully independent researcher.

5.13 Chapter Conclusions

Artificial intelligence is a key element of the Mars Avatar Project architecture, because it makes it possible to compensate for the physically unavoidable communication delay between Earth and Mars. In the proposed concept, the AI does not replace the human but provides autonomous execution of local actions within the goals set and the constraints defined in advance. This approach combines the advantages of human decision-making with the capabilities of modern autonomous robotic systems and is consistent with the current direction of development in space robotics.

Chapter 6. Mission AI Architecture

> *The single most underdeveloped layer in today's planetary robotics is not the robot and not the operator — it is the intelligence that coordinates a fleet.*

6.1 The Place of Mission AI in the System

The preceding chapters define Mission AI as an “intelligent dispatcher” between the operator and the fleet but do not describe its internal design. Yet this layer is the least-developed area in current programs (see Section 3.8) and therefore the project's principal original contribution. This chapter specifies a reference architecture for Mission AI: five layers, the goal-package protocol, decision categories, and quality metrics.

6.2 Five-Layer Reference Architecture

Layer 1. Goal Interpreter. Transforms the operator's goal (“explore the southern part of the crater”) into a formal task: a measurable result, constraints, success criteria, and an allowable level of autonomy. If the goal is ambiguous, the interpreter does not “guess” but returns clarifying options to the operator — this is cheaper than erroneous execution under a latency of tens of minutes.

Layer 2. Fleet Planner. Decomposes the task into subtasks and distributes them among platforms according to their specialization, position, charge, and current load. The base mechanism is market-based (auction) task-allocation algorithms: each platform “bids” a price reflecting its cost, and decentralized consensus protocols such as CBBA guarantee conflict-free allocation even under incomplete fleet connectivity [29]. The choice of a decentralized mechanism is fundamental: the fleet must remain operational if any node fails, including the central planner itself.

Layer 3. Shared World Model. A single digital model of the environment to which all platforms write: a geometric layer (maps, obstacles), a semantic layer (rock types, infrastructure objects), and a dynamic layer (weather, energy, equipment state). A copy of the model is synchronized to Earth and serves as the basis for the operator's virtual environment (Section 9.5) — the operator always works with the latest agreed “snapshot” of Mars.

Layer 4. Execution Monitor. Compares actual progress against the plan, detects deviations (a task running longer than planned, a sensor giving contradictory data, a platform becoming unavailable), and initiates replanning within its authority. It inherits the approach of NASA's onboard planner-executives: Remote Agent on Deep Space 1 (1999) — the first AI to autonomously operate a spacecraft [26]; the CASPER/ASE pairing on the EO-1 satellite autonomously replanned science observations for over a decade [27].

Layer 5. Safety & Approval Gate. The final filter before any action is executed: it classifies actions into categories (see Section 6.4), blocks prohibited ones, queues risky ones for Earth approval, and maintains an immutable log of decisions with a “why” explanation — the basis for later review and for the explainability requirement of Section 12.7.

6.3 The Goal Package Protocol

The packet principle for commands, described in detail later in Section 7.7, is formalized here. The goal package is the minimal unit of exchange between Earth and Mission AI:

- **goal_id, priority, deadline** — identification and place in the queue;
- **objective** — a measurable result (“a sample of mass ≥ 50 g delivered from sector B12”);
- **constraints** — prohibitions and limits (zones, slopes, energy consumption, wear);
- **success_criteria** — formal completion conditions, automatically verifiable;
- **autonomy_level** — which classes of decisions may be made without Earth (see Section 6.4);

- **fallback** — prescribed behavior when execution is impossible (return, wait, proceed to the next goal).

The response package is symmetric: result, log of key decisions with justifications, deviations from the plan, and updates to the world model. The protocol's formality is a condition of verifiability: both the Stage I simulation trials and the certification before Stage III reduce to checking the system's behavior over a set of goal packages.

6.4 Decision Categories and Approval Levels

Class	Example Actions	Who Approves	Typical Latency
A — critical	First drilling in a new rock type; movement on a slope above threshold; any action near another platform; irreversible consumption of a resource	Operator on Earth	Hours (comms cycle)
B — standard	Route in a surveyed zone; sampling by a validated procedure; nominal charging	Mission AI, with report to Earth	Seconds–minutes
C — internal	Stabilization, thermal regulation, local obstacle avoidance, self-diagnosis	The platform's onboard AI	Milliseconds

Class boundaries are not a constant but a parameter of the goal package: as trust statistics accumulate, the operator may move routine actions from Class A to Class B. This provides a controllable trajectory of increasing autonomy — instead of a binary choice between “the human controls everything” and “the AI decides everything.”

6.5 Behavior Under Degradation

The architecture defines a degradation hierarchy:

1. **Loss of the link with Earth** — the fleet completes Class B/C tasks within active packages, and no new Class A tasks are begun (consistent with Section 5.10).
2. **Loss of the central Mission AI node** — platforms continue their current subtasks under the decentralized protocol and gather at a pre-designated rally point.
3. **Loss of an individual platform** — its subtasks return to auction and are reallocated; the maintenance robot receives a diagnostic task.

Each degradation level must be a separate Stage I test scenario.

6.6 Mission AI Quality Metrics

- **Goal Completion Rate** — the share of goal packages completed against success criteria without reformulating the goal;
- **Intervention Rate** — the average number of operator interventions per package (the principal metric of autonomy maturity; the target trend is a monotonic decline from stage to stage);
- **Safe-Stop Rate** — the frequency of transitions to safe mode (high indicates immature perception, zero is suspiciously aggressive tuning);
- **Coordination Overhead** — the share of fleet time spent on coordination rather than work;
- **Explanation Adequacy** — the share of Class A/B decisions whose explanation the operator accepts without further queries.

These metrics translate the success criteria of Section 10.9 from qualitative statements into measurable quantities and make it possible to compare versions of the system objectively across stages.

6.7 Open Research Problems

- **Verification of learned components:** formal methods (Section 12.4) apply to classical logic but not to neural-network perception; hybrid schemes of “learned perception + verifiable decision-making” are needed.
- **Sim-to-real transfer:** Martian conditions cannot be fully reproduced on Earth; a methodology for quantifying the gap is required.
- **Coordination under local-network fragmentation:** the behavior of auction protocols when the fleet is split into isolated groups for extended periods.
- **Long-term world-model drift:** the accumulation of errors in the shared model over years of operation and protocols for its “rebuild” from fresh data.

Each of these problems is a research program in its own right, and it is these — not the appearance of the robots — that define the project's true critical path.

Chapter 7. Interplanetary Communication and Mission Control

> *In interplanetary exploration, communication is not simply a channel for transmitting information — it is a fundamental architectural constraint.*

7.1 The Role of the Communication System

In traditional robotics, communication provides data exchange between operator and machine. In the interplanetary environment its role is much broader. The communication system must provide:

- transmission of mission goals;
- receipt of scientific data;
- monitoring of equipment status;
- coordination of multiple robots;
- safe operation under long delays.

The communication architecture becomes one of the key elements of the entire mission.

7.2 Physical Constraints

The distance between Earth and Mars changes constantly. As a result, the one-way signal travel time is approximately:

Distance	Delay (one way)
Minimum	~4 minutes
Average	~12 minutes
Maximum	~22 minutes

These values are determined by the speed of light and cannot be eliminated by improving equipment [4] [5]. Consequently, the Mars Avatar Project architecture is built with this fundamental property in mind.

7.3 Communication Architecture

Each layer performs its own function and does not duplicate the others.

Fig. 7.1. The layers of the Mars Avatar Project communication system

7.4 Mission Control Center

The control center is the intelligent coordination node. Its tasks:

- distributing tasks among robots;
- analyzing incoming data;
- planning operations;
- monitoring resources;
- interacting with the science team;
- preparing new commands.

Mission Control works with goals, not with the individual movements of each robot.

7.5 Mars Relay Network

Orbital relays make it possible to:

- increase surface coverage;
- reduce the likelihood of losing communication;
- organize data exchange among robots;
- provide storage of part of the information until the link is restored.

As the infrastructure develops, the number of relays can grow [6][7].

7.6 The Local Mars Network

After the orbiters receive data, communication takes place within a local network. It may unite rovers, construction robots, drones, laboratories, power stations, and future crewed bases. Thus, a distributed robotic infrastructure takes shape.

7.7 Command Transmission

Instead of continuous control, a packet principle is used. A command contains a goal, constraints, a priority, an allowable execution time, and criteria for successful completion. For example:

> *Mission Goal: Collect Rock Sample · Location: Sector B12 · Priority: High · Safety: Maximum · Return Data*

Having received such a package, the local AI plans the execution on its own.

7.8 Transmission of Scientific Data

Returned to Earth are: images, terrain maps, spectral measurements, telemetry, AI reports, and event logs. Transmission can occur with varying degrees of priority.

High priority: emergency messages; the state of equipment; critical scientific discoveries.

Low priority: archival images; operation logs; diagnostic information.

7.9 Operation During Loss of Communication

Communication may be temporarily unavailable for various reasons: solar interference, technical malfunctions, constraints of orbital geometry. In such cases the system must:

1. save current data;
2. enter safe mode;
3. complete only safe operations;
4. wait for communication to be restored.

This reduces the likelihood of losing equipment.

7.10 Network Scaling

In the early stages the system may consist of a few robots. Later, the architecture allows expansion to a distributed network. All platforms operate as a single coordinated system.

Fig. 7.2. Scaling of the distributed avatar network

7.11 Cybersecurity

The interplanetary network must provide:

- authentication of commands;
- protection against data spoofing;
- verification of packet integrity;

- redundancy of communication channels;
- logging of critical actions.

Security is treated as an integral part of the architecture, not as an add-on feature.

7.12 Chapter Conclusions

The communication system in the Mars Avatar Project is not merely a means of transmitting information but the foundation of the entire control architecture. Because of the fundamental limits of the speed of light, control is built on the principle “goal → autonomous execution → feedback.” This approach makes effective use of the combination of human decision-making and the autonomous operation of robotic systems.

Chapter 8. Robotic Avatars

> *The robot is not intended to replace the explorer. It is intended to become the explorer's physical presence where the human body cannot safely operate.*

8.1 General Concept

At the heart of the Mars Avatar Project lies the idea of specialized robotic platforms — avatars — each designed to perform a particular class of tasks. Instead of building a single universal robot, the project envisions a modular ecosystem in which different types of platforms work together and complement one another. This approach is widely used in modern engineering, since specialized systems are often more effective than universal ones.

8.2 Core Requirements

Each robotic avatar must have the following characteristics:

- high autonomy;
- radiation tolerance;
- a modular design;
- the ability to receive remote software updates;
- a self-diagnostic system;
- a safe operating mode upon loss of communication;
- compatibility with the project's shared infrastructure.

8.3 Classes of Robotic Platforms

Scientific Rover

The primary research platform. Functions: geological research, drilling, sample collection, spectral analysis, cartography, ice prospecting. Equipment: a manipulator, high-resolution cameras, lidar, spectrometers, a drilling module, navigation sensors.

Construction Avatar

Purpose: infrastructure construction. Capabilities: installing solar panels, erecting structures, assembling modules, cable laying, site preparation. This is one of the key elements in creating a future base.

Cargo Robot

Designed for logistics. Main functions: hauling equipment, delivering spare parts, transporting samples, moving construction materials.

Drone

Aerial vehicles can perform reconnaissance, map building, route finding, equipment inspection, and monitoring the condition of assets. Given the thin Martian atmosphere, their design must account for the specifics of flight in these conditions.

Laboratory Unit

The autonomous laboratory performs chemical analysis, biological analysis, sample preparation, long-term storage of materials, and transmission of research results.

Maintenance Robot

Purpose: repairing other robots. Functions: diagnostics, module replacement, equipment cleaning, routine maintenance. This extends the service life of the entire system.

8.4 Modular Design

Each avatar consists of interchangeable modules: power, mobility, manipulator, sensor, communication, and the AI computer. This approach simplifies repair and upgrades.

Fig. 8.1. The modular structure of a robotic avatar

8.5 The Power System

Solar Panels

Advantages: high reliability; no consumable fuel; ease of operation. **Disadvantages:** dependence on illumination; the impact of dust storms.

Radioisotope Power Sources

Advantages: stable operation; independence from the time of day. **Disadvantages:** limited availability; complexity of development and use.

The specific choice depends on the mission type and power requirements. Practical confirmation of this choice comes from NASA's experience: the Opportunity rover, which ran on solar panels, was lost in 2018 to a global dust storm, whereas Curiosity and Perseverance, equipped with the MMRTG radioisotope source, continue operating regardless of illumination and dust [10][11][12].

8.6 The Sensor System

Each avatar must perceive its environment. A possible sensor suite:

- stereo cameras;
- lidar;
- radar;
- spectrometers;
- temperature sensors;
- inertial navigation;
- manipulator force sensors.

The combined operation of these sensors makes it possible to build a digital model of the environment.

8.7 Self-Diagnosis

Each robot continuously assesses battery charge, component temperatures, motor condition, link quality, and computing-system errors. Upon detecting a fault, the system can limit functionality, enter safe mode, notify the operator, or request servicing.

8.8 Robot Interaction

The collective work of specialized platforms is considered the most effective. For example: a drone maps the area; the scientific rover takes samples; the cargo robot delivers the container; the laboratory unit performs analysis; Mission Control receives the results. Each performs its own function.

Fig. 8.2. An example of specialized platforms working together

8.9 Scaling

The architecture allows gradual development.

Stage	Structure
Stage 1	1 operator → 1 robot
Stage 2	Mission Control → 5 specialized robots
Stage 3	Mission Control → 100 autonomous platforms
Stage 4	Planetary Robotic Infrastructure → thousands of interacting systems

This approach allows capabilities to grow without changing the base architecture.

8.10 Limitations

Robotic systems also have limitations:

- mechanical wear;
- dust damage;
- extreme temperatures;
- energy constraints;
- the need for periodic servicing.

Consequently, the project does not treat robots as failure-proof systems. Reliability is achieved through redundancy, modularity, and serviceability.

8.11 Chapter Conclusions

Robotic avatars are the physical layer of the Mars Avatar Project architecture. Instead of building one universal machine, the concept envisions specialized platforms united by a shared control system and autonomous AI. Modularity, distribution of functions, and the ability to scale gradually allow the architecture to be adapted to a variety of tasks — from scientific research to preparing infrastructure for future crewed expeditions.

Chapter 9. The Human–Machine Interface: From Traditional Control to Telepresence

> *The quality of exploration depends not only on the intelligence of the robot, but also on how naturally a human can interact with it.*

9.1 Introduction

One of the central tasks of the Mars Avatar Project is creating effective interaction between the human and the robotic system. Unlike traditional remote control, where the operator commands each movement of the robot, the proposed concept involves transmitting goals and intentions rather than individual motor commands. This requires developing interfaces that allow a person to quickly understand what is happening and to interact effectively with the system even under a large communication delay.

9.2 The Evolution of Control Interfaces

Development is proposed to proceed in stages.

Fig. 9.1. The evolution of human–avatar interaction interfaces

Stage 1 — Present-Day Technologies

In use: keyboard and mouse, game controllers, professional joysticks, touch panels, voice control. These technologies are already widely used in robotics and industry.

Stage 2 — Immersive Control

Additionally used: VR headsets, AR interfaces, spatial controllers, hand tracking, eye tracking. The operator gains a more natural picture of the working environment.

Stage 3 — Brain–Computer Interface (BCI)

As technology develops, brain–computer interfaces may be used. It is important to emphasize: the Mars Avatar Project does not assume that today's BCIs can fully replace traditional means of control. For the near term they are regarded as an additional channel of interaction.

9.3 Brain–Computer Interface

A BCI is a system that allows nervous-system signals to be used to interact with a computer. Two main directions exist today.

Non-Invasive BCIs

Examples: EEG, functional near-infrared spectroscopy (fNIRS), combined neural interfaces. Advantages: no surgical intervention, safety, accessibility. Disadvantages: limited accuracy, low information-transfer rate [13][14].

Invasive BCIs

These involve placing electrodes in neural tissue. Potential advantages: higher bandwidth, lower latency, more precise recognition of intent. However, such systems are at the research stage and require further development and safety evaluation [13][14].

9.4 Telepresence

Telepresence does not mean creating the illusion of being on Mars in real time; it means giving the operator the fullest possible picture of what is happening, given the unavoidable communication delay.

The operator receives images, three-dimensional maps, telemetry, analysis results, and AI reports. This allows informed decisions to be made even when data arrives with a delay.

9.5 The Role of Virtual Reality

VR can be used for planning operations, training operators, simulating missions, analyzing the environment, and visualizing routes. The virtual environment is built from data received from Mars.

9.6 Haptic Feedback

In the future, devices that convey the sensation of touch or resistance may be employed. Such technologies could improve task precision, but their use under interplanetary latency requires further research.

9.7 The Operator's Work

In the proposed architecture, the operator:

- formulates the goal;
- analyzes incoming data;
- evaluates the AI's proposals;
- approves mission-critical actions;
- adjusts the mission as needed.

Thus, the operator remains the director of the process, not the direct executor of every movement.

9.8 Limitations

Even as interfaces develop, objective limitations remain: communication delay, limited channel bandwidth, possible signal-recognition errors, the operator's cognitive load, and the need for training on the system. These limitations must be taken into account when designing the interface.

9.9 Development Roadmap

Stage	Capabilities
Today	Joysticks, keyboard, voice control, VR
5–10 years	Tighter VR integration, eye tracking, improved interfaces
10–20 years	High-performance BCIs as an additional channel of interaction
Long term	More natural forms of human–robot interaction (contingent on further scientific breakthroughs)

9.10 Chapter Conclusions

The human–machine interface is the connecting link between the operator and the robotic infrastructure of the Mars Avatar Project. The concept envisions gradual evolution: from present-day control tools to more natural forms of interaction, including prospective neural interfaces. At the same time, the fundamental limitation associated with the signal delay between Earth and Mars remains. Even the most advanced interfaces therefore do not remove the need for autonomous operation of the local AI; rather, they serve as tools for more effective goal setting, data analysis, and human decision-making.

Chapter 10. Technology Roadmap

> *A vision becomes an engineering project only when it is divided into achievable steps.*

10.1 The Principle of Staged Development

The Mars Avatar Project does not envision building the complete system in a single step. The concept is based on the gradual development of technologies, where each subsequent level builds on the results of the previous one. This approach makes it possible to:

- test hypotheses experimentally;
- reduce technical risks;
- use technologies that already exist;
- adapt the architecture as new solutions appear.

Fig. 10.1. The implementation stages of the Mars Avatar Project

10.2 Stage I — Concept Demonstration (2026–2030)

Goal: validate the core principles of the Mars Avatar Project under terrestrial conditions.

Main tasks: developing the software architecture; building the control center; integrating the VR interface; using existing robots; simulating a communication delay of 20–30 minutes; testing the autonomous AI.

Demonstration scenario: the operator is in a laboratory; the robot works at a remote test range; all commands pass through an artificial delay. The AI, on its own, plans a route, avoids obstacles, performs the assigned task, and returns a report.

Result: creation of the first experimental prototype of the architecture.

10.3 Stage II — Lunar Demonstration (2030–2035)

After successful terrestrial trials, the system can be adapted for use on the Moon. Why the Moon?

- a much shorter distance;
- the possibility of more frequent missions;
- the existence of international exploration programs;
- relatively simple logistics.

At this stage it is possible to test autonomous navigation, control of multiple robots, infrastructure construction, and long-duration system operation.

10.4 Stage III — First Robotic Missions on Mars (2035–2045)

At this stage the architecture is applied directly on Mars. Possible tasks:

- building landing pads;
- preparing the power infrastructure;
- creating storage depots;
- geological research;
- scouting sites for future bases.

The operator now manages not a single robot but the entire mission.

10.5 Stage IV — Robotic Infrastructure

As experience accumulates, individual platforms are united into a single network. Possible elements: power stations, automated warehouses, repair stations, transport hubs, science laboratories, autonomous construction complexes. In effect, the planet's first robotic infrastructure emerges.

10.6 Stage V — Support for Crewed Missions

Once the infrastructure exists, safer crewed expeditions become possible. By that time, robots can prepare a landing pad, deploy solar power stations, check the equipment, build up resource reserves, and prepare habitation modules. Thus, the first crews arrive in a partially prepared environment.

10.7 The Long-Term Outlook

In the longer term, the architecture can be adapted for other objects in the Solar System: the Moon, Phobos, Deimos, Europa, Titan, asteroids. It is important to emphasize that this is a direction for further research, not a ready mission plan.

10.8 Technology Readiness

Component	Maturity Level
Robotic platforms	High
Interplanetary communication	High
Autonomous navigation	Medium–high
Local AI	Medium
Multi-robot systems	Medium
Non-invasive BCIs	Medium
High-performance BCIs	Low–medium
Full telepresence	Long-term goal

This table is not an official TRL assessment; it presents a qualitative classification of technology maturity within the concept.

10.9 Success Criteria

Each stage must conclude with an objective verification of results. Example criteria:

Stage I: the robot performs a task under an artificial communication delay; the AI operates safely without operator involvement.

Stage II: several robots coordinate joint work; the architecture's reliability is confirmed.

Stage III: successful autonomous operation on Mars; completion of scientific tasks; confirmation of equipment reliability.

10.10 Principal Risks

At every stage the following must be considered: technical limitations, AI reliability, power supply, communication delay, development cost, and the effects of the Martian environment. The transition between stages is therefore possible only after the successful completion of the previous one.

10.11 Chapter Conclusions

The Mars Avatar Project is treated as a long-term research and development program, not a single mission. The proposed roadmap allows the key elements of the architecture to be verified in sequence — from a terrestrial prototype to a robotic infrastructure capable of supporting future crewed expeditions. Each stage is based on the principle of gradually reducing uncertainty: new technologies are introduced only after the experimental verification of previous solutions. This approach follows the practice of major engineering programs and makes the concept more realistic and suitable for discussion.

Chapter 11. Quantitative Estimates

> *An architecture without numbers is a story. An architecture with numbers is an engineering argument.*

11.1 Method and Caveats

All estimates in this chapter are order-of-magnitude figures based on open data from completed and operational missions. Their purpose is not budgeting but a test of the concept's central economic argument: that robotic infrastructure is an order of magnitude cheaper than a crewed expedition for a comparable volume of work performed. All figures should be re-verified against primary sources before use in presentations.

11.2 Cost of Robotic Missions: Actual Data

Mission	Program Cost	Comment
Mars Pathfinder + Sojourner (1997)	~$0.3B	First rover; demonstration of low-cost landing
Spirit + Opportunity (MER, 2004)	~$0.8B (prime mission)	Two rovers; Opportunity operated for 14 years
Curiosity (MSL, 2012)	~$2.5B	900 kg, MMRTG, still operating
Perseverance + Ingenuity (2021)	~$2.7B (full lifecycle)	1,025 kg; Ingenuity helicopter ~$0.085B
Mars Sample Return (cancelled, 2026)	estimate grew from ~$3–4B to $8–11B	Funding cancelled by the U.S. Congress in January 2026 [22]

Two conclusions follow from the table. First, the cost of a flagship robotic platform of the Perseverance class is ~$2–3 billion, of which a substantial share is one-time development cost: serial production of identical platforms lowers the unit cost. Second, the history of Mars Sample Return is an important cautionary tale: the growth of the estimate from ~$3–4B to $8–11B led to the program's cancellation [22]. The return architecture (ascent from Mars, orbital rendezvous) proved to be the principal source of complexity. MAP does not have this complexity in principle: avatars do not return, and data is transmitted over communication links.

11.3 Cost of a Crewed Expedition: Range of Estimates

No official budget for a crewed Mars program exists. Reference points come from adjacent programs and independent analyses: the Apollo program, adjusted to current prices, is estimated at roughly $260–280 billion; the construction and operation of the ISS at about $150 billion; independent estimates of a full crewed Mars program based on architectures such as NASA DRA 5.0 [25] give a range from ~$100 to ~$500 billion, depending on the number of expeditions and the degree of hardware reuse. Even the lower bound of this range exceeds the cost of a flagship robotic mission by one to two orders of magnitude.

11.4 Model Calculation: A Fleet of Avatars vs. an Expedition

Consider the Stage III fleet from the roadmap: 10 specialized platforms (2 science rovers, 3 construction robots, 2 cargo robots, 1 laboratory, 1 maintenance robot, 1 drone set) plus 2 orbital relays.

Item	Estimate	Basis
Development of 5 platform types	$8–12B	~$2–2.5B for the first unit of a type (analogous to MSL/Mars 2020)

Item	Estimate	Basis
Serial units (5)	$2–4B	a serial copy is several times cheaper than the first (MER analogy: two rovers in one program)
Relays (2)	$1–1.5B	Mars Reconnaissance Orbiter class
Launches (4–6 heavy LVs)	$0.5–1.5B	commercial heavy launch vehicles
Ground segment and operations, 10 years	$2–4B	analogous to MSL/Mars 2020 operating budgets
TOTAL	**≈ $14–23B**	**versus ≥ $100B for a crewed program**

Even under conservative assumptions, a fleet of ten platforms with a ten-year operating cycle proves 5–10 times cheaper than the lower estimate of a crewed program. Moreover, the comparison is biased in favor of the human case: the expedition budget does not include the landing and ascent infrastructure that — by the logic of Stage V — robots must build in advance in any event.

11.5 Mass Constraint: EDL

Landing on Mars (Entry, Descent, Landing) is the most severe mass constraint. The proven maximum landed payload is ~1 tonne (Curiosity, Perseverance, the sky-crane scheme). Crewed architectures of the DRA 5.0 class require landing modules of tens of tonnes [25] — a technology that has never been demonstrated. MAP's robotic platforms fit within the proven range of ≤1 t per vehicle, which allows the program to begin on existing landing technology. The advent of super-heavy systems (Starship class) would lift the constraint for robots as well — but MAP does not depend on it.

11.6 Energy Budget

An MMRTG source provides ~110 W of electrical power at the start of life [10] — sufficient for a science rover, but one to two orders of magnitude below the needs of a construction robot (several kilowatts when operating manipulators and moving cargo). Possible solutions: combining the MMRTG with buffer batteries for peak loads; deployable solar arrays with mechanized dust removal; low-power nuclear reactors of the Kilopower class — the KRUSTY ground prototype (1–10 kW) was successfully tested in 2018 [24]. Energy is the bottleneck specifically of the construction scenario, not the science scenario, and should be a priority of Stages I–II.

11.7 Communication Bandwidth

The current relay via orbiters returns data on the order of hundreds of megabits to a few gigabits per sol per rover — adequate for telemetry and images, but limiting for the 3D models and video required by the interfaces of Chapter 9. The key change is laser communication: NASA's DSOC experiment (2023–2025) demonstrated 267 Mbit/s at a distance of 31 million km and 8.3 Mbit/s at 2.7 AU — an increase of one to two orders of magnitude over radio links at comparable terminal mass [23]. For MAP this means that “dense” telepresence (streams of 3D maps and video, delayed but not bandwidth-starved) is technologically achievable within the horizon of Stages II–III.

11.8 Summary Comparison

Criterion	Crewed Expedition	Fleet of Avatars (Stage III)
Program Cost	≥ $100B	≈ $14–23B
Landed mass per module	tens of tonnes (not demonstrated)	≤ 1 t (proven)

Criterion	Crewed Expedition	Fleet of Avatars (Stage III)
Duration of surface operation	~500 days (return window)	10+ years (MER, MSL experience)
Risk to life	high	none
Return	mandatory (principal source of complexity)	not required
On-site reaction speed	seconds	minutes–hours (compensated by autonomy)
Scientific flexibility and intuition	maximal	limited by AI and sensor capabilities

The honest conclusion from the table is symmetric: on cost, risk, and operating duration the robotic architecture wins by an order of magnitude; on reaction speed and on-site scientific intuition the human remains without peer. This confirms the position of Chapter 13: MAP is not a replacement for crewed missions but a way to make them cheaper and safer by taking on the preparatory and routine work.

Chapter 12. Analysis of Risks, Limitations, and Ethical Aspects

> *Every ambitious engineering concept must be evaluated not only by its potential, but also by its risks and limitations.*

12.1 Introduction

Any architecture for an interplanetary robotic system faces numerous technical, organizational, and ethical challenges. The purpose of this section is not to prove the project's absolute feasibility, but to identify the key limitations that must be taken into account as it develops further. It is precisely the understanding of limitations that turns a concept into an engineering research program.

12.2 Technical Risks

Equipment Reliability

The Martian environment differs greatly from Earth's. The main factors: dust storms, extreme temperatures, radiation, mechanical wear, limited repair options. Equipment must therefore be designed for high fault tolerance and autonomous diagnostics.

Power Supply

Any autonomous system depends on energy. The main risks: declining solar-panel efficiency, dust accumulation, battery degradation, failure of power modules. The power system must therefore provide redundancy and different power sources depending on the mission's tasks.

Artificial-Intelligence Failure

The AI may misinterpret a situation, err in classifying objects, choose a suboptimal route, or encounter a situation absent from its training data. Mission-critical decisions must therefore remain under human control, and autonomous actions must be confined to predefined bounds.

12.3 Communication Risks

Communication between Earth and Mars can be disrupted for various reasons: solar activity, hardware malfunctions, damage to relays, data-transmission errors. The architecture must provide:

- command buffering;
- local data storage;
- a safe mode;
- automatic resumption of operation once the link is restored.

12.4 Software Risks

Modern autonomous systems comprise millions of lines of code. Possible problems: programming errors, faulty updates, component incompatibility, accumulation of computational errors. To reduce risk, the following are recommended:

- a modular architecture;
- independent testing;
- redundancy of critical components;
- formal verification of individual algorithms where possible.

12.5 Cybersecurity

Although interplanetary systems are less accessible to external interference, security remains an important task. It is necessary to ensure cryptographic protection of commands, operator

authentication, protection of telemetry, logging of actions, and software version control. Security must be treated as part of the architecture from the very start of development.

12.6 Limitations of the Concept

The limitations of the project itself should be noted. The Mars Avatar Project does not claim that:

- today's AI can fully replace the human;
- existing BCIs provide full telepresence;
- all the necessary technologies are already available.

On the contrary, the document proposes a research roadmap that shows which components already exist and which require further development.

12.7 Ethical Questions

The development of autonomous robotic systems raises a number of questions. For example:

- What degree of autonomy is acceptable?
- Which decisions must always be approved by a human?
- Who bears responsibility for the system's errors?
- How can the transparency of AI decision-making be ensured?

Within the Mars Avatar Project, the following principle is proposed:

> *The human retains responsibility for strategic decisions, while autonomous systems act only within predefined rules and goals.*

12.8 Economic Risks

Building such an architecture will require prolonged research, international cooperation, significant financial resources, and the development of space infrastructure. The project should therefore be viewed as a long-term research program rather than a short-term commercial initiative.

12.9 Scientific Limitations

Many elements of the project have not yet been experimentally confirmed. For example: scalable multi-robot systems for interplanetary conditions; long-duration autonomous operation without human involvement; widespread use of high-performance BCIs in space missions. The following are therefore needed:

- experimental prototypes;
- trials on Earth;
- lunar demonstration missions;
- gradual verification of the architecture.

12.10 The Principle of Engineering Honesty

One of the key principles of the Mars Avatar Project is an open classification of technologies by readiness level:

- 🟢 **Established** — existing, proven solutions.
- 🟡 **Projected** — expected directions of development.
- 🔴 **Long-Term Research** — ideas requiring fundamental scientific breakthroughs.

This approach helps avoid inflated expectations and makes the concept more transparent to the scientific community.

12.11 Chapter Conclusions

Any concept for exploring Mars must account not only for potential benefits but also for limitations. The Mars Avatar Project treats risks as an integral part of the engineering process. Instead of trying to ignore the difficulties, the project proposes staged hypothesis testing, gradual technology development, and continuous safety assessment. This approach follows the practice of developing complex technical systems, where reliability is achieved through the sequential verification of solutions, not by assuming their infallibility.

Chapter 13. Conclusion and Prospects

> *The greatest advances in exploration begin not with certainty, but with a well-founded question.*

13.1 The Principal Conclusion: Investing in Presence, Not in a Destination

The traditional logic of space programs is built around a destination: “a program to fly to the Moon,” “a program to fly to Mars.” Each such program is an expense: its result is exhausted once the goal is reached. The Mars Avatar Project proposes the opposite logic. The object of investment is not a flight but a technology of presence: the ability of human intelligence to act at any point in the Solar System through autonomous robotic intermediaries. Such a technology has the properties of an asset:

- **it accumulates:** every executed goal package, every hour of autonomous operation, every adjusted decision-class boundary (Section 6.4) raises the maturity of the system for all future applications;
- **it transfers:** the architecture contains nothing specifically “Martian” — Mars merely sets the numerical values of parameters (delay of 4–22 min, gravity of 0.38 g, atmospheric composition);
- **it scales:** from one operator and one robot to a planetary robotic infrastructure without changing the base architecture (Section 8.9).

A crewed expedition possesses none of these properties. This does not make it unnecessary — it makes it the second step, not the first.

13.2 Why “Humans First” Is Poor Engineering, Not a Bold Dream

The limitations of crewed missions — radiation, duration, life support, cost of ≥ $100B, mandatory return — are examined in detail in Chapters 2 and 11. What matters here is the conclusion that follows from them. Sending a human into an unprepared environment is not an act of courage; it is a transfer onto the crew of risks that infrastructure was obliged to remove. No mature engineering practice works this way: reconnaissance, site preparation, and the deployment of power and communications precede the human. This is exactly the work performed by the robotic layer.

The correct formulation is therefore not “humans are a dead end,” but: the human is too expensive and too vulnerable an instrument for first contact with an environment. The human remains irreplaceable where real-time scientific intuition and reaction to the wholly unforeseen are required — Table 11.8 honestly records this advantage. But paying for intuition with life support, radiation risk, and a return architecture makes sense only once the environment has been prepared and the routine work has already been taken over by robots.

13.3 Mars as a Proving Ground, Not as a Goal

In the logic of “presence technology,” the choice of Mars is explained not by romance but by methodology:

1. **The 4–22-minute delay is an honest stress test.** A system designed for Martian latency automatically covers the Moon (seconds) and scales to the asteroid belt and the outer planets (tens of minutes to hours).
2. **Maximal scientific return per unit of risk.** Water, geology, the question of life — Mars justifies the cost of the first deployment.
3. **Existing infrastructure.** The relay network, proven ≤1 t landing schemes, and operational autonomous systems (AutoNav, AEGIS) mean the starting base already exists [6][8][28].

But the result of the program is measured not only in Martian data. The result is a verified, certified architecture of presence, applicable to the next object with a change of parameters — not of principles.

13.4 Key Conclusions of the Study

1. Autonomy is not an option but a physical necessity. The speed of light makes direct teleoperation impossible over interplanetary distances; local AI is mandatory (Chapter 5).

2. The human remains in command. The Human-in-Command principle is preserved at every level: goals, constraints, and critical decisions belong to the human; execution belongs to the system (Sections 4.3, 6.4).

3. The least developed layer is fleet coordination. Not the robots and not the interfaces, but Mission AI — the intelligence coordinating a heterogeneous fleet — is the principal space of the project's original contribution (Chapter 6).

4. The architecture must develop in stages. Terrestrial prototype → lunar demonstration → Martian missions → infrastructure → support for expeditions; transitions between stages occur only against measurable criteria (Chapters 10, 6.6).

Fig. 13.1. The development sequence of the Mars Avatar Project architecture

13.5 Presence Technology Beyond Mars

Transferring the architecture to other objects is not a distant fantasy but a direct consequence of its parametric nature:

- **the Moon (delay ~1.3 s):** the degenerate case — the architecture operates in near-real time; the natural proving ground of Stage II;
- **asteroids (minutes to tens of minutes):** a regime identical to the Martian one, with microgravity added;
- **Europa, Titan (tens of minutes to hours):** the limiting case, demanding maximal autonomy; it is here that the accumulated trust statistics (Section 6.4) become decisive.

Each new object requires new platforms (the physical layer) but not a new architecture (the intelligence layer). Herein lies the fundamental economics of the approach: the cost of each subsequent world is lower than that of the previous one, whereas in the crewed paradigm each subsequent world is more expensive.

13.6 A Closing Thought

The history of exploring the world is a history of instruments. Ships made the oceans reachable; aircraft, the continents; computers, the space of thought. Robotic avatars are the next instrument in this line. But their true significance is not that they “fly instead of the human.” It is that, for the first time, the presence of the human mind is separated from the presence of the human body — and therefore ceases to be bound to any single planet. Mars is only the first application. The asset is the technology of presence itself.

> *The future of planetary exploration may depend not only on where humans can travel, but on how effectively human intelligence can be extended through intelligent machines.*

Appendix A. References and Literature

Below are the sources supporting the key technical claims of this document. The numbers in square brackets in the chapter text ([1], [2], etc.) refer to the corresponding entries in this list. The list does not claim to be an exhaustive scholarly review and should be regarded as a starting point for further verification.

For Chapter 2. The Challenge of Exploring Mars

[1] ESA, “The radiation showstopper for Mars exploration” — a review of cosmic-radiation risks for long-duration missions, including data from the ExoMars Trace Gas Orbiter and the NASA Twins Study. esa.int

[2] Cucinotta F.A., Kim M.Y., Chappell L., “How Safe Is Safe Enough? Radiation Risk for a Human Mission to Mars,” PLOS ONE, 2013 — a quantitative estimate of the risk of exposure-induced death (REID) for a Mars mission based on the NASA model. Available via PubMed Central (PMC3797711).

[3] Cucinotta F.A., Durante M., “Cancer risk from exposure to galactic cosmic rays: implications for space exploration by human beings,” The Lancet Oncology, 2006, 7: 431–435.

[4] NASA, ASCEND / NTRS, “Communication Delays, Disruptions, and Blackouts for Crewed Mars Missions” — an analysis of communication delay (up to ~22 minutes one way) and periods of complete signal blackout during solar conjunction. ntrs.nasa.gov (20220013418).

[5] ESA, Mars Express Blog, “Time delay between Mars and Earth” — an illustration of the minimum (~4 min) and maximum (~24 min) signal delay. blogs.esa.int/mex.

For Chapters 4 and 7. Architecture and Interplanetary Communication

[6] NASA Science, “Mars Relay Network” — a description of the operational network of relay orbiters (Mars Reconnaissance Orbiter, Mars Odyssey, MAVEN, ESA Trace Gas Orbiter, Mars Express) and their role in transmitting data from the Martian surface. science.nasa.gov/mars/mars-relay-network.

[7] NASA/JPL, “The Mars Relay Network Connects Us to NASA's Martian Explorers” — a technical description of the Deep Space Network and the scheme for relaying commands and telemetry through orbiters. jpl.nasa.gov.

For Chapter 5. Artificial Intelligence and Autonomous Navigation

[8] Verma V. et al., “Autonomous robotics is driving Perseverance rover's progress on Mars,” Science Robotics, 2023 — data on the share of autonomously driven distance (88% of 17.7 km in the first Martian year) and the records of the AutoNav system. doi.org/10.1126/scirobotics.adi3099.

[9] NASA/JPL, “NASA's Self-Driving Perseverance Mars Rover 'Takes the Wheel'” — a description of how AutoNav works: building a 3D terrain map, detecting obstacles, and planning a route without operator involvement. jpl.nasa.gov.

For Chapter 8. Avatar Power Systems

[10] NASA/JPL, “Mars 2020 Perseverance Launch Press Kit — Power” — technical specifications of the MMRTG radioisotope power source (about 110 W at start of life, 14-year design life). jpl.nasa.gov.

[11] Scientific American, “Why NASA's Perseverance Mars Rover Uses Nuclear Energy” — a comparison of the MMRTG with solar panels and an account of the Opportunity rover, lost to the 2018 dust storm.

[12] Marspedia, “Radioisotope Thermoelectric Generators: Advantages and Disadvantages” — a comparison of radioisotope power sources and solar panels, including the effect of dust devils on the solar arrays of the Spirit and Opportunity rovers.

For Chapter 9. Neural Interfaces (BCI)

[13] Waldert S., “Invasive vs. Non-Invasive Neuronal Signals for Brain-Machine Interfaces: Will One Prevail?”, Frontiers in Neuroscience, 2016 — a comparison of invasive and non-invasive neural-signal acquisition methods by resolution, bandwidth, and risk level. PMC4921501.

[14] “Brain–computer interfaces in 2023–2024,” review article, Brain-X, Wiley, 2025 — an up-to-date review of the accuracy–invasiveness trade-off in modern BCI systems. onlinelibrary.wiley.com.

For Chapter 3. Positioning Relative to Existing Work

[15] ESA, “METERON — Multi-Purpose End-To-End Robotic Operation Network” — an overview of the program of experiments in controlling ground robots from the ISS (2011–2019). esa.int.

[16] ESA, “Analog-1: ESA's interplanetary teleoperations experiment” — control of the Interact rover from the ISS by astronaut L. Parmitano, November 2019. esa.int.

[17] Schmaus P. et al., “Preliminary Insights From the METERON SUPVIS Justin Space-Robotics Experiment,” IEEE Robotics and Automation Letters, 2018 — supervisory goal-based control of a humanoid robot from orbit.

[18] Oleson S., Landis G. et al., “HERRO: Human Exploration using Real-time Robotic Operations,” NASA Glenn Research Center / AIAA, 2011 — the concept of teleoperating Martian robots from Mars orbit.

[19] Lester D., Thronson H., “Human space exploration and human spaceflight: Latency and the cognitive scale of the universe,” Space Policy, 2011 — an analysis of latency as a key factor in telerobotics.

[20] Bualat M. et al., “Surface Telerobotics: Development and Testing of a Crew-Controlled Planetary Rover System,” NASA Ames / AIAA, 2013–2014 — control of the K10 rover from the ISS.

[21] XPRIZE Foundation, “ANA Avatar XPRIZE” — results of the telepresence avatar-system competition (2018–2022); winner — Team NimbRo, University of Bonn. xprize.org.

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[30] GITAI Inc. — demonstrations of autonomous robotic manipulators on the ISS (S1, 2021; external arm S2, 2024) and development of lunar platforms. gitai.tech.

For Chapter 6. Mission AI Architecture

[26] Muscettola N., Nayak P., Pell B., Williams B., “Remote Agent: to boldly go where no AI system has gone before,” Artificial Intelligence, 1998; flight experiment on Deep Space 1, 1999.

[27] Chien S. et al., “Using Autonomy Flight Software to Improve Science Return on Earth Observing One,” Journal of Aerospace Computing, 2005 — multi-year autonomous operation of the CASPER/ASE planner on the EO-1 satellite.

[29] Choi H.-L., Brunet L., How J.P., “Consensus-Based Decentralized Auctions for Robust Task Allocation,” IEEE Transactions on Robotics, 2009 — the CBBA algorithm for task allocation in multi-robot systems.

For Chapter 11. Quantitative Estimates

[22] Voosen P., “NASA's Mars Sample Return mission is dead,” Science, January 2026 — cancellation of MSR funding after the cost estimate grew to $11 billion. science.org.

[23] NASA/JPL, “Deep Space Optical Communications (DSOC)” — results of the laser-communication demonstration (2023–2025): 267 Mbit/s at 31 million km; 8.3 Mbit/s at 2.7 AU. jpl.nasa.gov.

[24] NASA, “Kilopower / KRUSTY” — ground testing of a low-power nuclear reactor (1–10 kW) for space applications, 2018. nasa.gov.

[25] Drake B.G. (ed.), “Human Exploration of Mars Design Reference Architecture 5.0,” NASA-SP-2009-566 — NASA's reference architecture for a crewed Mars mission.

Note

This list reflects the state of technologies and scientific data at the time the document was prepared and requires periodic updating as new publications appear. All quantitative estimates (TRL levels, risk percentages, equipment specifications) should be checked against primary sources before use in presentations or publications intended for a technical audience.